AMYGDALA $z \mapsto z^2 + c$

A Newsletter of fractals & $\mathcal{M}$ (the Mandelbrot set)

Issue #20
May 13, 1990

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SLIDES (C20)

This issue's slide supplement features one slide by A.G. Davis Philip and three by me (Rollo Silver): the first fractal slides I've made.

803:

"A Scene from Seahorse Valley" by A.G. Davis Philip.

I produced the next three slides using Dave Platt's MandelZot 2.0, but they were not photographed from a color monitor screen.

I used MandelZot to save each picture as an image file (in Macintosh PICT format). I then sent the images on floppy disks to PhotoTime Computer Slide Services in Palo Alto, where they created the slides using an Agfa Slide Writer film recorder.

That device has two modes: 4096×2732 and 2048×1366. Registration is constant, and odd sizes are blocked out by Quickdraw. To help overcome these limitations I decided to choose the pixelation to be 1024×683 — exactly one half of 2048×1366 to minimize "chunkiness". I forgot to record the pixelation of #2300 and 2301; sorry!

2300:

22-Legged Ant (Rollo Silver). This is a reprise of the last image in the 40-slide LaMance series, using the MandelZot smooth CLUT (Color Look Up Table). Center = -.7239834 + .2867198i × (suidar) 1.2×10^5. ER (Escape Radius) = 2, DL (Dwell Limit) = 2000.

2301:

Map48 (RS). This is a reprise of Peitgen & Richter's Map 48 (from The Beauty of Fractals), using the smooth CLUT. Center = –.7454286 + .1130088i × 1.96×10^5, ER = 2.5, DL = 1000.

Please turn to SLIDES on page 2.

COMPUTING SECTIONS OF THE CUBIC CONNECTEDNESS LOCUS

Notes on a talk given at the Computer Systems Laboratory Colloquium, Stanford University, March 7, 1990

— Rudy Rucker

A map in the plane is some system for finding an image P' of each point P. One might, for instance, stretch the plane by moving each P twice as far from the origin O, or one might rotate the plane, moving each point P to a point P' some fixed number of degrees further clockwise.

If we think of each point in the plane as a complex number $z=x+iy$, one can get a very interesting map by taking z into z^2. In terms of points, the operation of letting P' be the square of P works by actually squaring the length from P to the origin and by then rotating P to P' in such a way that the angle between OP' and the x-axis is exactly twice the angle between OP and the x-axis.

If f is a map in the plane, and f maps z into z, I can express this either by writing $z' = f(z)$ or by writing $z \xrightarrow{f} z'$. Given an f and a z, we can define a sequence z_n by:

$$z_0 = z$$
$$z_{n+1} = f(z_n).$$

Please turn to RUCKER on page 2

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SLIDES, continued from page 1.

2314:

JDJ midget (RS). This is the same midget that appears in John Dewey Jones' slide #37 (distributed with Amy #2), but shown here with less magnification. I created a MandelZot custom CLUT which reveals a pleasing interior image suggesting an Indian ceremonial feather fan. Center = $-1.99638 \times 3.6\times10^4$, DL = 4095, ER = 2.0. PX = 1638×1093 which is (4096×2732) × $^2/_5$.

Several people have raised valid objections to the way I've defined "magnification". I still think that "the reciprocal of the radius of the largest circle that can be inscribed in the view rectangle" is a useful parameter to help specify a picture — but I've decided to sidestep the terminological controversy by calling that quantity "suidar" (faute de mieux) rather than "magnification".

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RUCKER, continued from page 1

In terms of *f*,

$$z \xrightarrow{f} z_1 \xrightarrow{f} z_2 \xrightarrow{f} z_3 \xrightarrow{f} z_4 \xrightarrow{f} \cdots$$

The norm $|z|$ of $z=x+iy$ is gotten as $\sqrt{x^2+y^2}$ and is equal to the distance of z from the origin. If $|z_n|$ becomes arbitrarily large as n increases, we say that z goes to infinity under the map *f*, which we can symbolize as $z \xrightarrow{f} \infty$. If z does not go to infinity under the map *f*, we write $z \xrightarrow{f} FINITE$, and say that z is *bounded* under the map *f*. Note that $z \xrightarrow{f} FINITE$ does not mean that the z_n sequence approaches a specific limit; more characteristically, the z_n will cycle among being close to some finite number of different limits. $z \xrightarrow{f} FINITE$ simply means that there exists some real *BOUND* so that for all n, $|z_n| < BOUND$.

The *Julia set* for a map *f* is defined as the set of all z in the plane which are bounded under *f*. Symbolically, the Julia set for *f* is $\left\{ z : z \xrightarrow{f} FINITE \right\}$.

The map f_c given by $f_c(z) = z^2 + c$ has been widely studied. By translating the origin, any quadratic map $A \cdot w^2 + B \cdot w + C$ can be put into the form $z^2 + c$, with z a linear function of w. We give the Julia set for f_c the name $\mathcal{J}_c$:

$$\mathcal{J}_c = \left\{ z : z \xrightarrow{f} FINITE \right\}.$$

All the $\mathcal{J}_c$ are symmetric about the origin, meaning that if the complex number $z=x+iy$ is in $\mathcal{J}_c$, then the complex number $-z=-x-iy$ is in $\mathcal{J}_c$ as well. Some Julia sets are connected with non-empty interiors (disklike), some are connected with empty interiors (linelike), and the others are totally disconnected (dustlike). $\mathcal{J}_c$ being *totally disconnected* means that if A and B are in $\mathcal{J}_c$, there is a disk around A whose boundary contains no member of $\mathcal{J}_c$ and which excludes B. No Julia set ever breaks into two or more disklike pieces to be connected without being totally disconnected. Given this fact and the fact that the $\mathcal{J}_c$ have symmetry around the origin, the intuition is not surprised to learn that $\mathcal{J}_c$ is connected if and only if the origin (0,0) is a member of $\mathcal{J}_c$.

If we think of varying c through all of its complex values, we can think of a c-plane which has a $\mathcal{J}_c$ set defined at each of its points. Benoit Mandelbrot had the idea of looking at the locus of all the c's for which $\mathcal{J}_c$ is connected. This is the Mandelbrot set, $\mathcal{M}$. Symbolically:

$$\mathcal{M} = \{c : \mathcal{J}_c \text{ is connected}\}$$

$$= \left\{c : (0,0) \xrightarrow{f_c} FINITE\right\},$$ because $\mathcal{J}_c$ is connected if and only if (0,0) in $\mathcal{J}_c$;

$$= \left\{c : c \xrightarrow{f_c} FINITE\right\},$$ because if $z_0 = (0,0)$, $z_1 = c$ under f_c.

In a recent paper entitled "The Cubic Connectedness Locus", John Hubbard and a collaborator discuss how to generalize this to the cubic case. I have not yet seen this paper, only having been told of it by Charles Gunn, so some of my comments may not be as sharp as possible.

The maps we study will be called the maps f_{kc}, given as $f_{kc}(z) = z^3 - 3 \cdot k \cdot z + c$. By translating the origin, any cubic map $A \cdot w^3 + B \cdot w^2 + C \cdot w + D$ can be put into the form $z^3 - 3 \cdot k \cdot z + c$, with z a linear function of w. (The reason for casting the linear coefficient in the form $-3 \cdot k$ will become clear shortly.) For each f_{kc} we can define a Julia set $\mathcal{J}_{kc}$ by:

$$\mathcal{J}_{kc} = \left\{z : z \xrightarrow{f_{kc}} FINITE\right\}.$$

Unlike the quadratic case, these Julia sets are generally not symmetric. Some of them are connected, some are disconnected but not totally disconnected (made up of numerous separate individually connected disks), and some are totally disconnected. It has been proved that $\mathcal{J}_{kc}$ is in fact connected if and only if both the complex numbers $k = a + ib$ and $-k = -a - ib$ are in $\mathcal{J}_{kc}$. As $\mathcal{J}_{kc}$ is not symmetric, it may happen that only one of k or $-k$ is in $\mathcal{J}_{kc}$. $\mathcal{J}_{kc}$ is connected only when both of these critical points are in $\mathcal{J}_{kc}$.

What Hubbard and his co-workers call the *Cubic Connectedness Locus* — but which we may as well call $\mathcal{H}$ — is the four-dimensional set of all complex pairs k and c such that $\mathcal{J}_{kc}$ is connected:

$$\mathcal{H} = \{(k,c) : \mathcal{J}_{kc} \text{ is connected}\}; \text{ or}$$

$$= \left\{(k,c) : k \xrightarrow{f_{kc}} FINITE \text{ and } -k \xrightarrow{f_{kc}} FINITE\right\}.$$

It is known that $\mathcal{M}$ is connected in the plane. I do not know if it has been proved that $\mathcal{H}$ is connected in 4D space, but from what I have seen this seems likely.

There are various ways to look at $\mathcal{H}$. Charles Gunn of the Geometry Supercomputer Project in Minneapolis has made a video of a particular three dimensional cross-section of $\mathcal{H}$. What I have been doing in my recent programming is to look at various two dimensional cross-sections of $\mathcal{H}$: cross-sections taken for various fixed values of k.

If the value of k has been temporarily fixed, the cross-section of $\mathcal{H}$ at k is analogous to the Mandelbrot set, so I call it $\mathcal{M}_k$:

$$\mathcal{M}_k = \{(c : \mathcal{J}_{kc} \text{ is connected}\}$$

$$= \left\{c : k \xrightarrow{f_{kc}} FINITE \text{ and } -k \xrightarrow{f_{kc}} FINITE\right\}$$

In the software I have designed, the user has control of a cursor in the k-plane, meaning that each cursor position selects a two dimensional value of $k = a + ib$. Whenever you press k, you see $\mathcal{M}_k$: the k-section of the cubic connectedness locus. By slightly varying a and/or b, one can look at k-sections near each other, and try to visualize stacking them one atop the other.

If $k = 0 + 0i$, one gets a degenerate $\mathcal{M}_k$ with fourfold symmetry. If $|k|$ is large, (about one or two), one gets an empty $\mathcal{M}_k$. All the $\mathcal{M}_k$ have symmetry around the origin, meaning that if $c = u + iv$ is in $\mathcal{M}_k$, then $-c = -u - iv$ will be in $\mathcal{M}_k$, too.

The appearance of the $\mathcal{M}_k$ is quite interesting. One often sees small replicas of the quadratic Mandelbrot set, though sometimes with wedges cut out of it. Looking at successive sections, one often gets the impression of the $\mathcal{M}_k$ being like a cross-section of a three-dimensional Mandelbrot shape, with buds all over it. But of course $\mathcal{H}$ is four-dimensional, and this shows up in the fact that many of the bud cross-sections have pieces missing from them. Presumably these missing pieces have inappropriate four-dimensional coordinates for intersecting $\mathcal{M}_k$.

As an aid to mathematical visualization, I think of it this way. $\mathcal{H}$ is like a three-dimensional solid which is free to move pieces of itself to arbitrary time locations. Thus if a section of a bud seems to have the right half missing, we might think of the left half of the bud as being in Monday and the right half of the bud as being in Tuesday, with your cross-section being computed at the Monday time coordinate. I use time not at all in a physical sense here, but simply for the vividness of the image.

Now I explain how I compute my $\mathcal{M}_k$. The computation is done by fixing $k = a+ib$ and then varying $c = u+iv$ and checking whether $k \overset{f_{kc}}{\rightarrow} FINITE$, and $-k \overset{f_{kc}}{\rightarrow} FINITE$. On the basis of what I learn while doing this checking, I will assign an $\mathcal{M}_k$ color (c) to the pixel representing that $k \overset{f_{kc}}{\rightarrow} FINITE$ if for all n less than *MAXITERATION*, the n-th image of k has norm less than *BOUND*. *BOUND* can be taken to be any number strictly larger than $\sqrt{2}$ (I use 7), and a *MAXITERATION* of even fifty is sufficient to see $\mathcal{M}_k$'s gross features.

Now, assuming $k = a+ib$ has been set, my computation of the $\mathcal{M}_k$ color (c) for a fixed $c = u+iv$ takes place as follows (this pseudocode description is not fully optimized):

```
initialize:
    iteration = 0;
    tx = a;
    ty = b;
    a3 = -3 * (a*a - b*b);
    b3 = -3 * (2 * a * b);
and then iterate:
    x2 = tx * tx;
    y2 = ty * ty;
    xa = x2 - y2 + a3;
    yb = 2*tx*ty + b3;
    temp = xa*tx - yb*ty + u;
    ty = xa*ty + yb*yx + v;
    tx = temp;
    iteration = iteration + 1;
until x2 + y2 > BOUND or iteration =
    MAXITERATION, saving iteration as
    iteration1;
and then reinitialize:
    iteration = 0;
    tx = -a;
    ty = -b;
    a3 = -3 * (a*a - b*b);
    b3 = -3 * (2 * a * b);
and iterate the same computation until x2 + y2 >
BOUND or iteration = MAXITERATION, saving
iteration as iteration2;
If iteration and iteration2 both equal
MAXITERATION, then Mk color(c) = 0.
Otherwise,
    Mk color(c) =
    min(interation1,iteration2).
```

A set which I am particularly interested in graphing is $\mathcal{NZK} = \{(k : \mathcal{M}_k \text{ is non-empty}\}$. As a partial approach to this, I have already adapted the algorithm above to compute

$$\mathcal{R} = \{(k : k \text{ is in } \mathcal{M}_k\}$$
$$= \left\{(k : k \overset{f_{kk}}{\rightarrow} FINITE \text{ and } -k \overset{f_{kk}}{\rightarrow} FINITE\right\}$$

Note $\mathcal{R}$: $\mathcal{M}_k$ :: $\mathcal{M}$: $\mathcal{J}_c$ in one sense, for:

$$\mathcal{R} = \{(k : k \text{ is in } \mathcal{M}_k\}$$
$$\mathcal{M} = \{(c : c \text{ is in } \mathcal{J}_c\}$$

Both are "diagonal" sets (as in Cantor's diagonal argument).

As an extension of the set $\mathcal{NZK}$ I would also like to map a coloring of the k-plane in which the color at k is a linear function of the area in pixels of the computed set $\mathcal{M}_k$. Presumably the $\mathcal{M}_k$ are measurable, and the k-plane area coloring will converge to a more and more precise pattern at higher resolutions. The value of the color map of the k-plane would be that if one wants to stack 2D cross-sections up to get a nice looking 3D object, it would probably be a good idea to have the change in area between successive slices be minimal. This could be done by choosing your k along a level path in the color map. Alternatively, choosing k along a path of maximal area change might be interesting as well.

☛ A program running the $\mathcal{J}_c$, $\mathcal{M}$, $\mathcal{J}_{kc}$, $\mathcal{M}_k$ and $\mathcal{R}$ computations in 16-bit or 32-bit fixed-point real or floating point formats will be available as the *Mandel* module of the product *James Gleick's Chaos: The Software*, to be released by Autodesk, Inc. in Summer, 1990. The software will be for IBM PC/XT/AT, PS/2 or compatibles with 640 KB RAM and EGA or VGA graphics. For information about this product you may call 1-880-525-2763, or write Autodesk, Attn: Chaos, 2320 Marinship Way, Sausalito, CA 94965.

A REQUEST FOR FRACTAL SOFTWARE

I wish to find programmers who could send me freeware/shareware/public domain, fractal, Julia/Mandelbrot set or any game - graphic on disk for the IBM XT/AT. Julia/Mandelbrot four-dimensional, etc. Unfortunately these are not available in Hungary. I am a beginner, and would like to learn more with your help. Please help me if you can.

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TUTORIAL: COMPLEX ANALYTIC GEOMETRY

— Rollo Silver

Here are solutions to the first two exercises posed in Amy #19 (page 7).

1. When does the following equation represent a straight line?

$$az + b\bar{z} + c = 0 \tag{1}$$

To keep things relatively simple I'll pull the rabbit out of the hat and give the answer straightway — something I usually don't like to do. In this case I think it'll focus attention through a maze of detail.

(1) represents a straight line if and only if:

$$|a| = |b| > 0 \tag{2a}$$

and

Some complex z satisfies (1). (2b)

Let's define a few quantities:

$$z = x + iy \tag{3a}$$

$$a = A + i\alpha \tag{3b}$$

$$b = B + i\beta \tag{3c}$$

$$c = C + i\gamma \tag{3d}$$

We then have $\bar{z} = x - iy$, and so equation (1) becomes:

$$(A + i\alpha)(x + iy) + (B + i\beta)(x - iy) + (C + i\gamma) = 0 \tag{4}$$

with all coefficients real. The real and imaginary parts of (4) must each be zero separately:

$$(A + B)x + (\beta - \alpha)y = -C \tag{5a}$$

$$(\alpha + \beta)x + (A - B)y = -\gamma \tag{5b}$$

We can now reformulate our theorem:

The set of points $\langle x, y \rangle$ satisfying (5a) and (5b) forms a straight line if and only if:

$$|a| = |b| > 0 \tag{6a}$$

and

At least one point $\langle x, y \rangle$ satisfies (5a) & (5b). (6b)

Let's proceed to our proof.

IF:

Let's suppose(6a) and (6b), and prove that the set of real number pairs $\langle x, y \rangle$ satisfying (5) represents a straight line.

We cannot have all four coefficients zero, for if they were: — $A + B = 0$, $\beta - \alpha = 0$, $\alpha + \beta = 0$, $A - B = 0$ — we would have $A = 0$ & $\alpha = 0$, hence $a = 0$, hence $|a| = 0$, contradicting (6a). We have three cases:

Case 1: The first equation is degenerate: A+B $= \beta - \alpha = 0$; but the second is not. In this case (5a) reduces to -C=0. We must then have C=0, otherwise no $\langle x, y \rangle$ would satisfy (5a), contradicting (6b). Then (5a) is satisfied by all pairs $\langle x, y \rangle$, while the set of points $\langle x, y \rangle$ satisfying (5b) is a straight line. Thus the set of points satisfying both equations is that straight line, Q.E.D.

Case 2: The second equation is degenerate, the first is not. This case is handled in essentially the same way as Case 1.

Case 3: Neither equation is degenerate. In this case each of the equations (5a) & (5b) represents a straight line. These two lines are either (a) parallel, (b) intersecting, or (c) the same.

They cannot be parallel, or the equations (5) would have no solution at all, contradicting (6b).

Let's suppose they intersect. Then equations (5) have a unique solution and so, as (I hope) you know from high-school algebra, the determinant of the equations (5) is non-zero, i.e. $D \neq 0$, where

$$D = \begin{vmatrix} A + B & \beta - \alpha \\ \alpha + \beta & A - B \end{vmatrix} \tag{7}$$

so $(A + B)(A - B) - (\beta - \alpha)(\alpha + \beta) \neq 0$, so $(A^2 - B^2) - (\beta^2 - \alpha^2) \neq 0$, so $|a|^2 - |b|^2 \neq 0$, so $|a| \neq |b|$, which contradicts (6a).

We are left with the fact that the straight lines must be the same, i.e. that the equations (5) represent a straight line, Q.E.D.

This concludes the "if" part of our proof. We must now consider the other part:

ONLY IF:

Suppose that the set of points $\langle x, y \rangle$ satisfying (5a) and (5b) forms a straight line, and let's prove (6a) and (6b).

Since these equations define a line, not a point, they are singular, *i.e.* the determinant (7) is zero: $D = 0$. It follows by an argument similar to that given below (7) that $|a| = |b|$, which is half of (6a). As to the other half, if we had $|a| = |b| = 0$ then all the coefficients of (5) would be zero, and the equations would either have no solution at all, or would be satisfied by all $\langle x, y \rangle$. Neither of these two possibilities is consistent with our assumption that the set of $\langle x, y \rangle$ satisfying (5) forms a line. This contradiction establishes the other half of (6a): that $|a| = |b| > 0$.

Now for (6b), then we're done. By hypothesis, the set of $\langle x, y \rangle$ satisfying (5) forms a line. For any point $\langle x, y \rangle$ on this line, z = x+iy satisfies (1). Q.E.D.

2. Write the equation of an ellipse, a hyperbola, a parabola in complex form.

Let's back off and start with a circle of radius r centered on the origin $\langle 0,0\rangle$. In real form, the equation of a circle with center $\langle 0,0\rangle$ and radius r is:

$$x^2+y^2=r^2 \tag{8}$$

Since $z=x+iy$ and $\bar{z}=x-iy$ we have:

$$x=\frac{z+\bar{z}}{2} \tag{9a}$$

$$y=\frac{z-\bar{z}}{2i} \tag{9b}$$

Substituting (9a) and (9b) in (8), multiplying out and simplifying, we get the equation of the circle in complex form:

$$z\bar{z}=r^2$$

If the circle has its center at (a,b), we have

$$(x-a)^2+(y-b)^2=r^2 \tag{10}$$

Applying (9a) and (9b) to (10):

$$((z+\bar{z})/2-a)^2+((z-\bar{z})/2i-b)^2=r^2 \tag{11}$$

Letting $\alpha=a+ib$, we have $\overline{\alpha}=a-ib$, and so $\alpha+\overline{\alpha}=2a$ and $\alpha-\overline{\alpha}=2ib$, which simplify (11):

$$(z-\alpha)\overline{(z-\alpha)}=r^2$$

Applying the same approach to an ellipse centered at the origin with major axis M and minor axis m:

$$\left(\frac{x}{M}\right)^2+\left(\frac{y}{m}\right)^2=1 \tag{12}$$

Applying (9a) and (9b) to (12), we get:

$$\left(z^2+\bar{z}^2\right)\left(m^2-M^2\right)+2z\bar{z}\left(m^2+M^2\right)=4M^2m^2$$

The approach should be clear by now, so I'll leave the remaining cases to the reader.

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Amber Lotus, a California publisher, is seeking fractal slides for the next edition of its annual *Fractal Cosmos* calendar. Graphics of high interest to the general public as well as to computer scientists, and transparencies or slides of high quality are the paramount requirements. Please send submissions by June 30th with a stamped self-addressed envelope for return, to:

Amber Lotus
1241 21st Street
Oakland, CA 94607

GLIMPSES OF A FUGITIVE UNIVERSE

A series of 14 prints of fractal images
created by Rollo Silver, imagist.
Some titles in the series are:

- Roses for Liyana
- Mosaic Peacock
- Vader's Heart
- 22-Legged Ant
- Unicellular Broccolus
- Green Ideas Sleep Furiously
- The Grail
- Ezekiel's Wheel
- Seahorse Quadrille
- A Wheel for Kathryn

These images have been rendered as high-quality Cibachrome prints of "Warp-3" resolution (2048 x 1366 pixels, or 2.8 million points total), mounted archivally. Each print is titled, dated, sequentially numbered, and signed by the imagist with a #4 Faber & Faber pencil.

Warp-4 (4096 x 2732) and Warp-5 (8192x5464) fractal prints up to 80" x 50" in size will be available within a year.

Price includes archival backing and film seal, mat and frame with a clear acrylic panel. It is too risky to ship framed prints with glass, hence the acrylic panel.

An 8x10 color print showing all fourteen images is available (ORDER #91500, price: $28.00 + $4.50 P&H).

Please write for complete price information.

Box 219
San Cristobal, NM 87564
☎ 505-586-0197

SPECIAL SLIDE MOUNTS AND FILM

—Robert W. Hill

You may have noticed that the slides [2401-2412] are not standard 35mm slides. The standard 35mm format has an aspect ratio different from that of TV and computer monitor screens, so that to photograph the entire height of a screen, extraneous and possibly distracting areas on the sides must be included. Alternatively, just the width may be included, but areas at the top and bottom are cut off.

Amygdala readers may be interested to know that slide mounts with the correct CRT aspect ratio are available from:

Heindl Masks'N'Mounts, Inc.
PO Box 150
Hancock, VT 05748

They have many styles of mounts; #441 is the one to order. They are $2 for a package of 15, or $10 for a package of 100.

I would also recommend the use of Polaroid "Presentation Chrome" 35mm film for photographing computer screens. This is a high contrast film intended for making slides for presentations. It requires E-6 processing, the same as Ektachrome. Side by side comparison with Ektachrome shows it to produce much superior color; no filtration is necessary or even desirable.

[from RWH letter of 10/5/89]

PRODUCT IDEA

"I'd love a good-quality tie with M-set pictures instead of the ubiquitous Paisley!"

—*John F. Moore*

FRACTAL VIDEOS?

Does anyone know of good fractal videos on videolaser disk, super ß, or Hi8 (high 8mm)?

—*H. Howard Hoffman*

CIRCULATION

As of May 13, 1990 Amygdala has 953 subscribers, 279 of whom have the supplemental color slide subscription.

RENEWAL

For 312 of you subscribers out there this is the last issue of your current subscription. I urge you to use the enclosed form to renew your subscription promptly to avoid missing anything.